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Maximizing Flyback Transformer Efficiencies in EV Battery Charger Applications

A look at several flyback transformer designs highlighting the advantages of using Litz wire to reduce AC power loss in the total coil design.

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Flyback transformers (like the BA60951CS Flyback Power Transformer) are a robust and highly efficient solution for electric vehicle (EV) battery charger applications. Their wide input voltage range and use of minimal additional components make them a cost-effective power conversion choice. The size of the transformer for these designs needs to be minimized as it is usually the biggest component on the PCB. However, minimizing the size of the transformer can lead to increased winding and core losses. A plus with flyback transformers is that they often offer multiple outputs, which can boost efficiency and provide more design flexibility. Conversely, this benefit makes it more difficult to minimize the size of the transformer while also balancing winding losses.

The trend to adopt smaller, lighter, faster and greener sources of energy has already taken place with switch mode power supplies (SMPS) that currently operate at faster switching speeds and with higher efficiencies. As these designs continue to advance for increasing use in vehicles to charge batteries, magnetic components must also advance to meet ever-evolving requirements and power efficiency goals.

This article covers several flyback transformer designs and highlights the advantages of using Litz wire to reduce AC power loss in the total coil design. Test results provided show the overall efficiency increases that can be achieved with Litz wire in terms of total core and coil losses.

Flyback Transformer Fundamentals

A flyback transformer doesn't match the classic definition of a "transformer." Rather, it operates essentially as a highly coupled inductor used to "store" energy. In a magnetics design, this is typically accomplished by putting a small air gap somewhere in the core magnetic flux path.

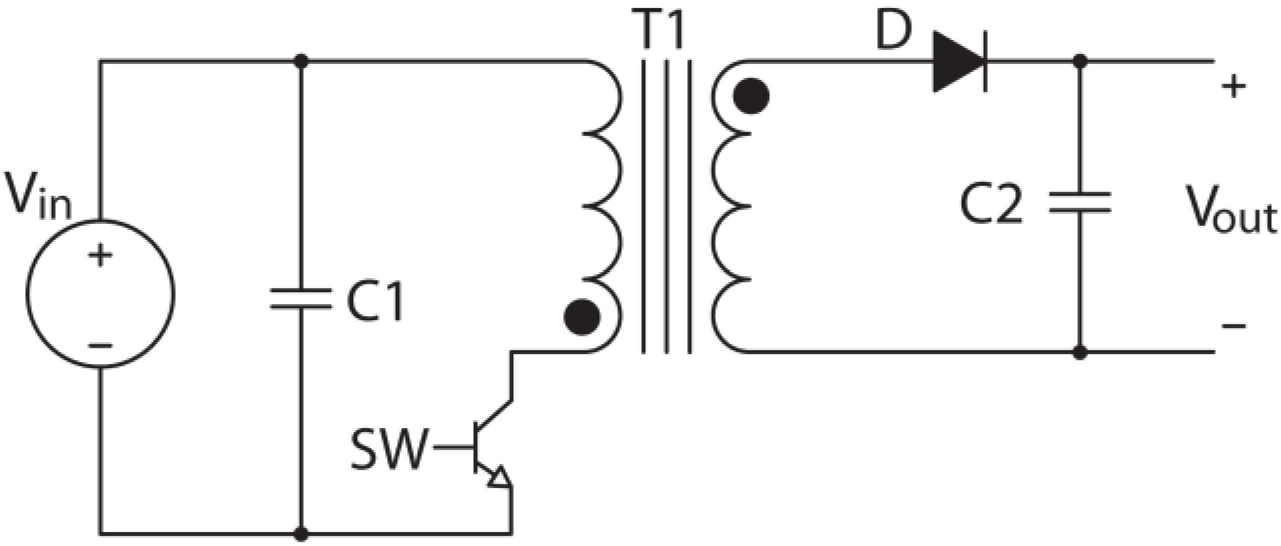

Figure 1: The flyback transformer circuit schematic. (Image courtesy of Bourns.)

When the primary switch (transistor) turns on in the flyback transformer, current energy in the primary winding is stored in the core and gap via ***E= L*I²***. (*E* is energy, *L* is primary inductance and *I* is primary current). When the switch opens, the primary winding polarity changes and the reverse-biased diode on the secondary side allows current to flow through the secondary winding. Stored primary energy moves to the secondary winding and ramps down.

To translate circuit operation to an actual design requires a combination of hand calculations, circuit simulators, analytical tools and the use of FEA (Finite Element Analysis) software. It is recommended to use computer tools such as Ansys PEXPRT and Ansys PEMAG that provide good representations of AC losses including eddy current skin, fringing and proximity effects.

The initial coupled inductor design below does not take high-frequency AC coil effects into consideration. The other designs presented incorporate various winding and layering techniques that reduce AC coil resistance for reduced power loss.

Design 1: 60 W Flyback Transformer

Design specifications (Table 1) for a 60W flyback transformer include five windings: one primary, three secondary and one auxiliary. To meet safety standards, secondary windings require reinforced insulated wire and can increase the size of the wire by up to 30 percent due to wire coating thickness. An EE30 3C94 Mn-Zn ferrite core is used.

AC and DC resistance were obtained from FEA simulation. AC resistance was multiplied by RMS current squared with DC loss found using DC current.

Total DC + AC copper loss, denoted P_{cu}:

$$P_{cu\ (total)} = 5.8\ W$$

Core loss is found using flux density ripple _ΔB_from Faraday's law (1.1), where V_{in} is the input voltage, A_c is the core area, D is the duty cycle, T the switching period and N_p is the number of primary turns:

[1.1]

$$V_L = -N\frac{d\emptyset}{dt}$$

$$\Delta B = \frac{V_{in}DT}{N_pA_c} = \frac{250\ x\ 0.11}{150\ x\ 10^3\ x\ 40\ x\ 60\ x\ 10^{-6}} = 0.097\ T$$

The core loss P_{fe} is calculated where V_c is the core's volume, f is the switching frequency, B_{max} is the peak flux density and K_c, α and β are Steinmetz parameters derived from core material properties:

[1.2]

$$P_{fe} = V_c K_c f^{\alpha} B_{max}^{\beta}$$

$$P_{fe} = (4020\ x\ 10^{-9})(2.9)(150\ x\ 10^{3^{1.39}})(\frac{0.097^{2.59}}{2}) = 0.072\ W$$

For Design 1, the total loss P_{total} equals copper loss plus core loss combined:

$$P_{total} = P_{cu} + P_{fe} = 5.8 + 0.072 = 5.782\ W$$

Core and coil loss generate heat, which affects core and coil at the highest level at the center of the component and radiates out to the surface where convection cooling occurs.

Design 1's total core + coil temperature was 98°C and a temperature rise of 76°C, far exceeding the specification.

Designs 2 & 3: Fringing and Proximity Effects

Design 2 takes into consideration fringing effects by changing the distance between the core gap and the start of the first winding. Fringing effects produce increases in AC resistance due to the bulging of magnetic flux around the core gap as opposed to traveling straight across it.

Distance is increased between core gap and coil using thicker bobbin material or spacer tape before the coil winding begins. This increases the Mean Length Turn (MLT) and DC resistance as well, but greater AC resistance reduction outweighs it. This technique results in an overall power loss of 4.15 W; a 30 percent reduction. Core loss is unchanged. Thermal simulation shows a 78°C temperature total, which is a 20°C reduction, but still too high.

Design 3 reduces the total number of coil wire layers to account for the proximity effect. The proximity effect is directly related to AC resistance and occurs where current distribution in one winding layer influences distribution in another. AC resistance is increased because the attraction of positive and negative charges alters the distribution of current so that it doesn't travel uniformly through the conductor and bunches to one side.

Decreasing layers reduces AC resistance of the primary winding and secondary winding 1. However, AC resistance increases for secondary windings 2 and 3 because of unavoidable bunching and uneven layering of primary and secondary 1. These trade-offs produce only marginally better overall loss in Design 3.

Design 4: Litz Wire Accounts for the Skin Effect

Previous designs reduced proximity and fringing effects; however, power loss reduction was not enough, and AC resistance remains large. Design 4 considers wire skin effects.

Wire carrying an AC current generates an AC field, which produces a cavitating wire effect called eddy currents. Eddy currents inhibit even distribution of electron current flow in the entire cross section of a wire, pushing current (density) to the outside of the wire. Because skin effects are frequency dependent, higher frequency AC current won't protrude as deep into the middle of the conductor.

To combat this, several to hundreds of strands of smaller wire are twisted together to create a larger diameter. Multiple wire strands have the capability of reducing AC resistance loss due to the skin effect. Higher frequency AC currents require more strands of wire. To reduce AC resistance in Design 4, Litz wire was used on all the secondaries. Thicker wire on the windings helped reduce copper losses.

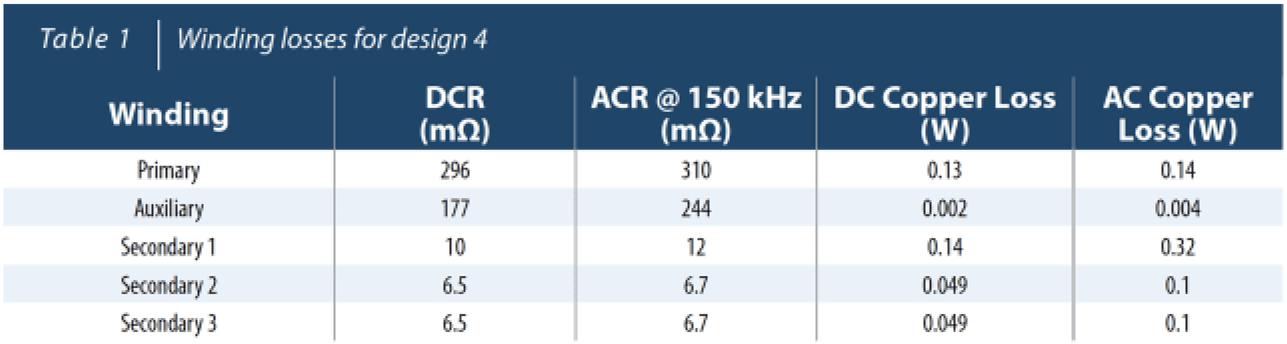

Table 1 | *Winding losses for design 4*

Winding	DCR (mΩ)	ACR @ 150 kHz (mΩ)	DC Copper Loss (W)	AC Copper Loss (W)
Primary	296	310	0.13	0.14
Auxiliary	177	244	0.002	0.004
Secondary 1	10	12	0.14	0.32
Secondary 2	6.5	6.7	0.049	0.1
Secondary 3	6.5	6.7	0.049	0.1

Table 1: Design 4 winding loss. (Image courtesy of Bourns.)

In Design 4, core loss remains unchanged, and total loss is less than the maximum power dissipation. It also resulted in an acceptable total temperature rise level.

Bourns tested the Litz wire flyback transformer design in an energy storage battery charger application development board. Tests showed that incorporating Litz wire delivered the greatest copper loss reduction and decreased the overall temperature and temperature rise of the final design. It also produced lower AC resistance than conventional wire. This resulted in reduction of power loss for the magnetic design iterations and directly related to increased efficiency of the total power supply circuit. Bourns offers extensive custom transformer design capabilities that include ferrite cores and Litz wire construction.

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